Mass Profiles and Shapes of Cosmological Structures
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CONSTRAINED SIMULATIONS OF DARK MATTER HALOS

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Abstract. The formation and structure of dark matter halos is studied by constrained simulations. A series of experiments of the formation of a $10^{12}h^{-1}M_{\odot}$ halo is designed to study the dependence of the density profile on its merging history. We find that the halo growth consist of several quiescent phases intermitted by violent events, with the density well approximated by the NFW profile during the former phases. We find that (1) the NFW scale radius R_s stays constant during the quiescent phase and grows abruptly during the violent one. In contrast, the virial radius grows linearly during the quiescent and abruptly during the violent phases. (2) The central density stays unchanged during the quiescent phase while dropping abruptly during the violent phase, and it does not reflect the formation time of the halo. (3) The clear separation of the evolution of an individual halo into quiescent and violent phases implies that its entire evolution cannot be fitted by simple scaling relations.

1 Introduction

The problem of the formation and structure of dark matter (DM) halos constitutes one of the outstanding challenges of theories of cosmic structure formation. N-body simulations of structure formation in a CDM cosmology find that the density profile of virialized halos is well approximated by the so-called NFW profile (Navarro, Frenk & White 1996). Analytical efforts of understanding the collapse of DM halos and the emergence of the NFW profile have focused on one of the two extreme scenarios. One is based on the spherical infall model (*e.g.* Hoffman

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& Shaham 1985) and the other on the merging scenario (*e.g.* Syer & White 1998). It has been shown that both models can adequately reproduce the NFW profile. Cosmological simulations show that halo formation in general proceeds via major mergers, yet simulations of halo formation via monolithic collapse reproduce the NFW structure as well. So, it is clear that a basic theory of gravitational collapse that can unite the seeming diametrically opposed models needs to be formulated. We have recently embarked on a series of constrained simulations aimed at shedding light on the origin and evolution of the NFW profile. The simulations are based on initial conditions constructed by means of constrained realizations of Gaussian fields (Hoffman & Ribak 1991), designed to run a series of controlled experiments of halo formation (Romano-Díaz *et al.* 2005).

It is generally accepted that the evolution of DM halos proceeds in two phases, of rapid and slow accretion (*e.g.* Wechsler *et al.* 2002). It is also known that an NFW structure is quickly established after the rapid phase and is preserved during the slow accretion. The role played by major mergers (*i.e.* rapid accretion) in establishing the NFW profle motivates us to conduct a set of numerical experiments in which the merging history is designed by constrained realizations, keeping their structure otherwise identical. Therefore any possible differences in the outcome of the simulations must be attributed to their merging histories. Such controlled numerical experiments can be easily performed by constrained simulations. We design a set of numerical experiments in which a given halo of mass $10^{12}h^{-1}M_{\odot}$ (where h is the Hubble's constant in units of 100 km s^{-1}Mpc^{-1}) is constrained to follow different merging histories.

2 Models

A set of five different models, *i.e.* experiments, is designed here to probe different merging histories of a $10^{12}h^{-1}M_{\odot}$ halo in an $\Omega_0 = 0.3$ OCDM cosmology. This halo is then modified to have different substructure on different mass scales and locations designed to collapse at different times. The spherical top-hat model is used here to set the numerical value of the constraints and the collapse time of substructures. This is used only as a rough guide as the various substructures are neither spherical nor isolated. Furthermore, the few constraints used here do not fully control the experiments. The nonlinear dynamics can in principle affect the evolution in a way not fully anticipated from the initial conditions. Even more important is the role of the random component of the constrained realizations (Hoffman & Ribak 1991). The models are designed as follows: Model A (the benchmark model) is based on two constraints. One is that of a $10^{12}h^{-1}M_{\odot}$ halo at the origin. This halo is embedded in a region corresponding to a mass of $10^{13}h^{-1}M_{\odot}$ in which the over-density is zero — a region corresponding to an unperturbed Friedmann model . These two constraints are imposed on all other models. Model B adds two substructures of mass $5 \times 10^{11}h^{-1}M_{\odot}$ within the $10^{12}h^{-1}M_{\odot}$ halo. Model C further splits each one of model B halos into two $2.5 \times 10^{11}h^{-1}M_{\odot}$ substructures. Thus, the benchmark halo is modified to follow two major mergers events on its way to virialization. Model D takes the Model A

and imposes six different small substructures of mass $10^{11}h^{-1}M_{\odot}$ scattered within the big halo. Model E attempts to simulate a more monolithic collapse in which a nested set of constraints, located at the origin, is set on a range of mass scales down to $M = 10^{10}h^{-1}M_{\odot}$. All models have been constructed with the same seed of the random field. All the density constraints constitute $(2.5 - 3.5)\sigma$ perturbations (where σ^2 is the variance of the appropriately smoothed field), and were imposed on a cubic grid of 128^3 grid of a co-moving length $L = 4Mpc/h$. The main halo consists of $\approx 10^6$ particles and is simulated by means of the FTM code.

3 Results

The analysis of the simulations is based on the construction of a halos catalog and by fitting an NFW density profile to individual halos. The evolution of the NFW parameters of the primary halo in each model is presented here. The evolution toward the final halo is studied by tracking in time the main branch that leads to this halo. The picture that emerges is that of a halo undergoing phases of slow and ordered evolution intermitted by episodes of rapid mass growth via collapse and major mergers. These are referred to as the quiescent and violent phases. The evolution of R_s, the virial radius R_{vir} and the mean density within R_s (ρ_s) is presented in Fig. 1. The trends found here are all reproduced when the fitting is done by a generalized NFW profile.

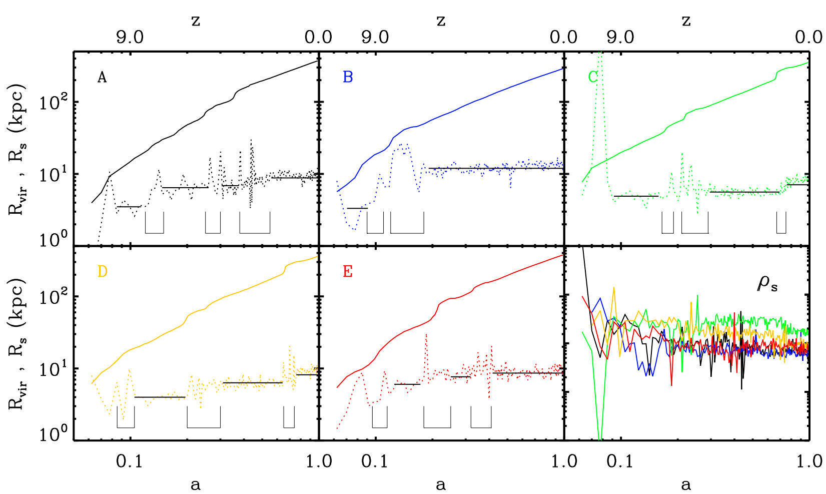

Fig. 1. Virial and scale radii behavior (continuous and dotted lines respectively) as function of the expansion parameter a for the five models. The discontinuous growths in R_s and R_{vir} match the violent phases that each halo passes through. The horizontal bars represent the mean value of R_s within the quiescent phases. The square brackets delineate the violent phases. The bottom right panel shows the evolution of ρ_s (in arbitrary units) with colors corresponding to the models in other panels.

4 Discussion

The dense time sampling of the halos evolution enables us to conclusively identify the trends in the evolution of the NFW parameters, some of which have been just hinted about in the literature so far. Here we focus on the evolution of R_s, $R_{\rm vir}$ and the central density. The main new results found here are: (1) The NFW scale R_s stays constant during the quiescent phases and changes abruptly during the violent ones. In contrast, $R_{\rm vir}$ is growing linearly in the quiescent and abruptly during the violent phases; (2) The value of R_s reflects the violent merging history of the halo, and it depends on the number of violent events and their fractional magnitudes, independent of the time and order of these events; (3) $\rho_{\rm s}$ stays unchanged during the quiescent phases and drops abruptly during the violent phases. The corollary is that $\rho_{\rm s}$ does not reflect the formation time of the halo; (4) The relative change in R_s is a nonlinear function of the relative absorbed kinetic energy within R_s in a violent event. (5) The fact that the evolution of a given halo consists of a few quiescent phases intermitted by violent episodes implies that simple scaling relations can be applied only to a single accretion trajectory but cannot be used to bridge and extend over a few such trajectories. We note, that the accretion trajectories in all models converge to the same value. This is a reflection of the large-scale structure shared by all the models and imposed by the constrained initial conditions.

The analogy between the halo evolution and thermodynamical processes has not escaped our attention. Equating the quiescent phases with adiabatic processes and the violent with non-adiabatic ones leads one to associate the behavior of R_s with that of the entropy. In this terminology the entropy remains constant in the quiescent phase and grows discontinuously in the violent phase. Also, the accretion trajectories play the role of adiabats and the system jumps from one adiabat to the other by a violent event, not unlike a shock wave.

The results obtained here pertain to the one halo studied in the framework of an OCDM cosmology. Yet, the conclusions reached from the set of experiments presented here are relevant to the understanding of halo formation in the general CDM cosmologies and in particular in the 'benchmark' ΛCDM cosmology.

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